Experimental Status of Beyond the Standard Model Collider Searches

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This is a brief review of experimental strategies for physics beyond the Standard Model based on the talk given in the "Physics at LHC" in Vienna, July 2004 [1]. The emphasis is on Tevatron thematology and experience.

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1 The high energy collider data to-date

The world-wide high energy collider data composition to-date is:

- proton-antiproton collisions
  - ~ 120 pb^{-1} at $\sqrt{s} = 1.8$ TeV.
  - ~ 300 pb^{-1} at $\sqrt{s} = 1.96$ TeV.
- electron-proton collisions
  - ~ 200 pb^{-1} at $\sqrt{s} = 320$ GeV.
- electron-positron collisions
  - ~ 1 fb^{-1} at $\sqrt{s}$ up to 209 GeV.

Results obtained by the experiments recording the data above are well in agreement with the Standard Model predictions. Of what I call our "high energy delinquencies" today, two I consider collider-wise curious. The first one is pending, and data from the Tevatron Run II will answer it: it is the need for a more precise top quark mass measurement from the CDF and DØ collaborations [1)]. The second is the understanding of the A^{0b}_{fb} measurement at LEP, covered in this workshop by Paul Langacker [4]. The former is critical in predicting new physics and the latter may suggest new physics affecting the third family.

Other excesses in different channels observed at CDF Run I/Run II, LEP, and HERA have been assessed statistically not significant. The theoretical and phenomenological part on beyond the standard model searches in the same workshop

1) The individual Run I most precise top mass measurent was reported by the DØ collaboration to be $m_{top} = 180.1 \pm 3.6 \pm 3.9 GeV/c^2$ [2]. The Run II most precise one was recently reported by the CDF Collbarotion to be $m_{top} = 173.5 + 4.1 - 4.0 GeV/c^2$ [3].

(by Joe Lykken, see these proceedings [5]), covers in detail the exotic tendencies today in collider physics. I would like to re-emphasize that most all are conceived within one kind or another of extra dimensions [6] and supersymmetric scenarios [7]. The strict or loose dualities between different frameworks for physics "beyond the standard model" have a direct experimental consequence: the final states and signatures of the models are very similar. This renders the characterization of an excess or a deviation, a fine and probably long challenge. To mention a couple of examples: the question "is it universal extra dimensions [8] or is it SUSY?" or "is it a Randall-Sundrum [9] graviton mode or a Z′ [10]" is not going to be answered immediately when the excess is observed. The results from all the collider data we have, together with the as yet unobserved Higgs, and in concilience with the data on the neutrino masses and the composition of the universe, point to a remainder in particle physics. But they do not point to the nature of it. There is something (probably a lot) more but it is tricky to say what it is. In high energy physics today when we talk about beyond the standard model phenomena, including supersymmetry, we talk about data at the edges or tails of the standard model distributions, be it large invariant masses or tails of missing transverse energy. It has become a cliché (albeit wise) that the accurate and precise determination of the standard model physics is crucial as a background to direct exotic searches and as an indirect probe of new physics.

2 The signature-model correspondence

The plethora of what the CDF collaboration (used as an example of the Tevatron experiments) calls "very exotic" searches is presented in the indicative listing (circa spring 2004) of signatures (corresponding to models) explored below:

- Di-Lepton Resonances
  - using ee, $\mu\mu$, $\tau\tau$
  - searching for Z', RS Extra Dimensions, Technicolor
- Same-Sign Di-Lepton Resonances
  - using $ee, \mu\mu, e\mu, \tau\tau$
  - searching for H^{++}
- Di-Lepton+Photon
  - using $ee\gamma, \mu\mu\gamma, \tau\tau\gamma$
  - searching for heavy leptons
- Di-Lepton+Di-jet
  - using $eejj$,$\mu\mu jj$, $\tau\tau\ jj$, $e\nu jj$, $\mu\nu jj$, $\tau\nu jj$, $\nu\nu jj$
  - searching for leptoquarks

– Photon+missing E_T
  * using $\gamma +$ missing $\mathrm{E_T}$
  * searching for ADD (see [5] and [13]) Graviton
– Photon+jet
  * using $\gamma+$ b-jet
  * searching for b'
– Highly-ionizing (slow) track
  * searching for H^{++}, H^{--}, monopoles, UEDs, stops and staus (and charged split SUSY-type R-hadrons more recently [11], [12]).

More signatures has been added to the list since, and are being investigated with the data.

Taking the reverse route, a particularly fashionable example is the signatures generated within the ADD model.

direct graviton production		
$e^+e^-, p\bar{p}$	$\longrightarrow$	$\gamma G,\ jG$
		ZG
		WG
		$f\bar{f}G$
virtual graviton exchange		
$e^+e^-, p\bar{p}$	$\longrightarrow$	$\gamma\gamma,\ WW,\ ZZ$
$q\bar{q}$		$\ell^+\ell^-$
$\ell^+\ell^-$		$q\bar{q}$
ep		$eX,\ \nu X$
$q\bar{q}$		$jj,\ t\bar{t}$

Table 1. Signatures generated within the ADD model in the cases of direct graviton emission and graviton exchange. G denotes a Kaluza-Klein graviton.

It is notable that LEP high energy experimentalists produced results on these searches almost as soon as the scenarios appeared: Higgs (e.g. visible mass analyses $e^+e^- \longrightarrow Z+$ missing energy) and GMSB type analyses (e.g $e^+e^- \longrightarrow \gamma+$ missing energy) were turned practically overnight into searches for direct G production in the ADD model. Anomalous $Z\gamma\gamma$ couplings, WW, $Z\gamma$ analyses (e.g. $e^+e^- \longrightarrow \gamma\gamma,\ VV$), were applied in searches for virtual G exchange effects and so did analyses with Bhabhas and other QED type of measurements.

The case of asymmetric or TeV^{-1} extra dimensions ([14] also see J. Lykken's review in these proceedings [5] and references therein) offers similar signatures. In

this case Kaluza-Klein Z, photon or gluon exchange affects the di-lepton, di-photon or di-jet cross sections at high p_T. Drell-Yan production at the Tevatron, HERA NC and CC deep inelastic scattering analyses, hadronic and leptonic cross sections and angular distributions at LEP 2, have all been studied by Cheung and Landsberg in the context of TeV^{-1} extra dimensions [15]. The limits obtained are shown in table 2. The overall limit on the compactification scale, $M_C > 6.8$ TeV has improved the one from the electroweak precision data. The estimated sensitivity reach at the Run II of the Tevatron and at the LHC using the Drell-Yan process is 2.9 TeV with 2 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and 13.5 TeV with 100 fb^{-1} of pp collisions at $\sqrt{s} = 14$ TeV (and assuming 3% overall uncertainty from systematics) correspondingly. Balázs and Laforge [17] showed that using the di-jet production, the LHC can probe $M_C \sim 5 - 10$ TeV. A Run II search at DØ using the invariant mass of di-electrons from 200 pb^{-1} (shown in figure 3) yields a 95% CL lower limit on M_C of 1.12 TeV.

	M_c^{95} (TeV)
LEP 2:	
hadronic cross section, ang. dist., $R_{b,c}$	5.3
μ, τ cross section & ang. dist.	2.8
ee cross section & ang. dist.	4.5
combined	6.6
HERA:	
NC	1.4
CC	1.2
HERA combined	1.6
TEVATRON I (120 pb^{-1}) :	
Drell-yan	1.3
Tevatron di-jet	1.8
Tevatron top production	0.6
Tevatron combined	2.3
All combined	6.8

Table 2. 95% CL upper limits on M_c for individual data sets and combinations.

3 Di-objects

In the example of searches using di-leptons in the final state resulting from an exotic object produced in $p\bar{p}$ collisions we note that the signature is usually well defined and triggered: two energetic, isolated, same flavor, opposite sign leptons. The summary of the Tevatron (CDF specific in this case) experience for this class of searches is that the Drell-Yan background, although irreducible, is well simulable and calculable and estimated to 5%. The remaining uncertainty is mainly from

resolution and acceptance since, after normalizing to the Z, the luminosity uncertainty drops out. At high invariant mass the dominant background and background uncertainty component is jets misidentified as electorns. Other "Fake" lepton backgrounds, *i.e.* pions decaying in flight, conversions, $K^+ \to \mu\nu$ as well as heavy flavor ($b \to c\ell\nu$) are not predicted but estimated from control data samples to ~30-50%. Cosmics in the muon channels have been always more of a problem than one might think for the Tevatron experiments and are estimated only to ~30-50%. W+jets, di-bosons and top backgrounds are eliminated with a high invariant mass requirement. In general the di-object exotic searches look for a resonance or a deviation in the di-object invariant mass spectrum, a cross section excess at large p_T, and modifications in the angular distribution of the final state objects especially at high invariant masses.

Representative spectra from CDF and DØ of di-lepton invariant mass spectra are shown in figures 1, 2, 3 and 4. In the DØ search both di-electrons and di-photons are considered simultaneously in the analysis and noted as "diEM".

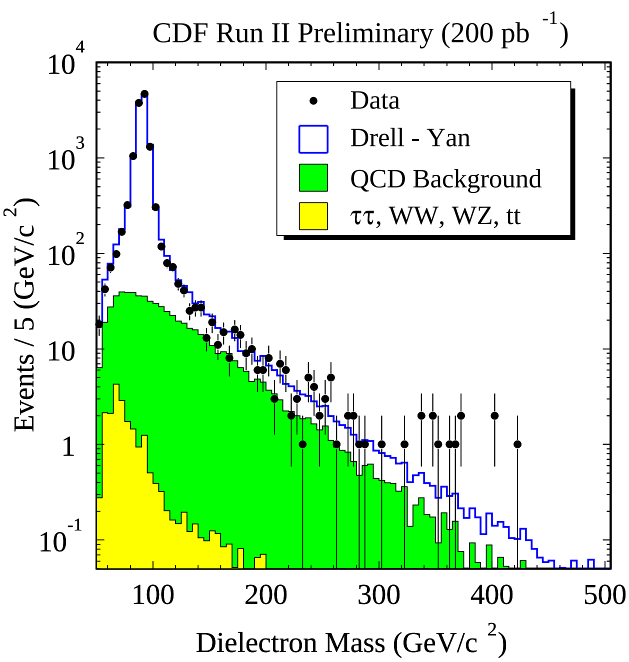

Fig. 1. Di-electron invariant mass spectrum comparison between data and estimated backgrounds at CDF RunII.

In the CDF di-lepton analyses the uncertainty on the total background estimate for $M_{\ell\ell} > 300$ GeV/c^2 is 40% for electrons, and 25% for muons. Systematic uncertainties sources are the luminosity, acceptance, energy scale and momentum resolution, selection efficiency, background statistics and normalization.

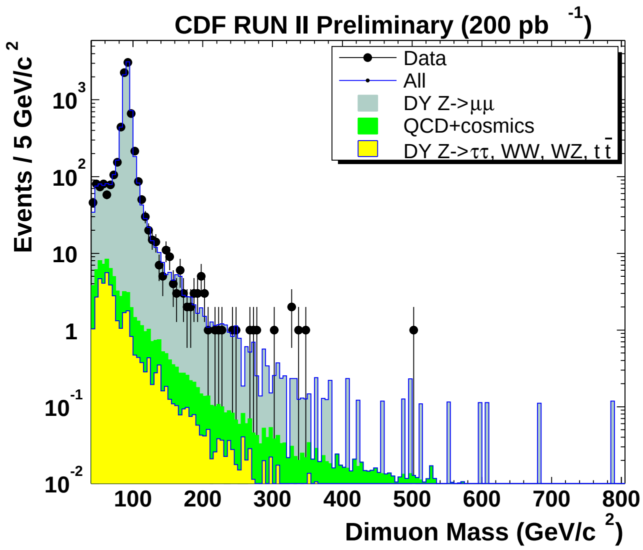

Fig. 2. Di-muon invariant mass spectrum comparison between data and estimated backgrounds at CDF Run II.

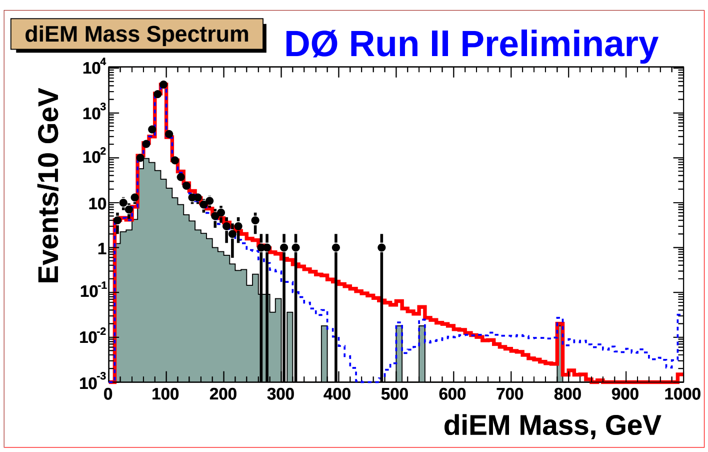

Fig. 3. Di-electron invariant mass spectrum comparison between data and estimated backgrounds at DØ Run II with 200 pb^{-1}. The dashed lines show the backgrounds plus the contribution from the TeV^{-1} signal. The deficit of expected events in the intermediate masses is due to negative interference of the first KK Z/γ mode with the Drell-Yan between the Z mass and M_C (0.8 TeV).

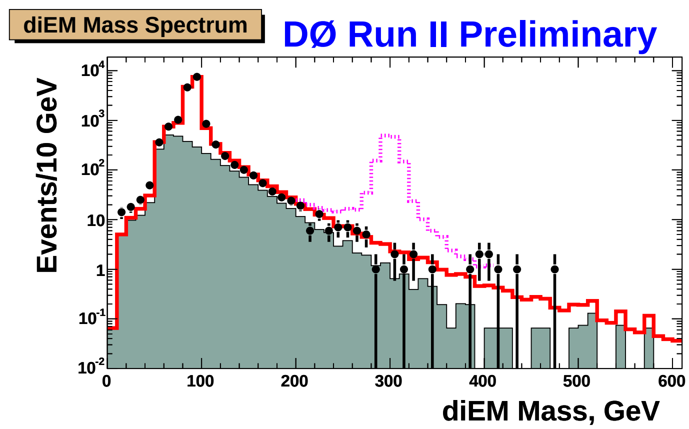

Fig. 4. Di-EM (electron and photon candidates) invariant mass spectrum comparison between data and estimated backgrounds at DØ Run II with 200 pb^{-1}. The shaded histogram indicates misidentified jets as EM objects. A signal for a RS-graviton with mass 300 GeV/c^2 and arbitrary cross section normalization is also shown.

The null result in the high mass same flavor di-lepton/di-photon (and not shown here di-jet) channels at the Tevatron is interpreted as 95% CL limits in a variety of scenarios: ADD extra dimensions (estimated for Run II and the LHC in table 3; results from 200 pb^{-1} of Run II are shown in table 4), Randall-Sundrum gravitons [9] (shown in figure 5), a multitude of Z' models (shown in figure 6) as well as technicolor particles and R-parity violating sneutrinos. It is interesting to note the reach improvement at the Tevatron in the case of the Z' search as a function of integrated luminosity: the 95% CL limit on the mass was 505 GeV/c^2, 640 GeV/c^2 and $\sim$800 GeV/c^2 using 20 pb^{-1}, 90 pb^{-1} and 200 pb^{-1}. The experiments use either a fit of the di-lepton invariant mass (CDF) or a mass window requirement and counting (DØ). A factor of 1.5 in mass reach is achieved with a factor of 10 in luminosity. At LHC (the examples are from CMS) less than 100 pb^{-1}, should be sufficient to discover Z' bosons of 1 TeV/c^2, a mass value which will likely be close to the final Tevatron reach. For integrated luminosity of 100 fb^{-1}, the Z' discovery reach is in the range between 3.4 and 4.3 TeV (no systematics are considered in these estimates) [18]. In the case of the di-electron final state analyzed in the context of RS gravitons, CMS with an integrated luminosity of 100 fb^{-1}, CMS will cover the region indicated in figure 7.

4 Mono-objects

Both in Run I [23], [24] and Run II [16] the Tevatron experiments use the missing energy plus a single jet as a probe for Kaluza Klein gravitons in the ADD

	M_S (TeV)		
	$n=2$	$n=4$	$n=6$
	$p\bar{p}$, $\sqrt{s}=2$ TeV, 2 fb^{-1}		
Di-Lepton	1.9	1.6	1.3
Di-Photon	2.4	1.9	1.6
Combined	2.5	1.9	1.6
	LHC, pp, $\sqrt{s}=14$ TeV, 100 fb^{-1}		
Di-Lepton	10	8.2	6.9
Di-Photon	12	9.5	8.0
Combined	13	9.9	8.3

Table 3. Estimated sensitivity reach on the ultaviolet cuttoff M_S at the Tevatron Run II and at the LHC [15].

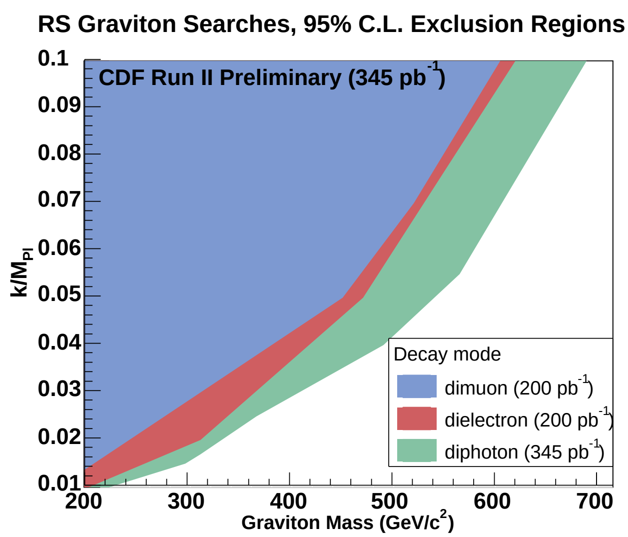

Fig. 5. 95% CL limits on the RS graviton mass-k/M_{Planck} plane from the CDF search in three di-object channels as indicated. The shaded area to the left of the corresponding curve is excluded.

scenario via the direct emission diagrams. The on-shell production of Kaluza-Klein gravitons produces a smooth missing energy distribution after convolution of the closely spaced KK spectrum with the PDFs. This, coupled with the large systematic uncertainties due to the jet energy scale and the highly polluted with instrumental backgrounds missing energy triggers, renders the channel challenging.

The 95% CL lower limits on the fundamental Planck scale M_D (in TeV) in

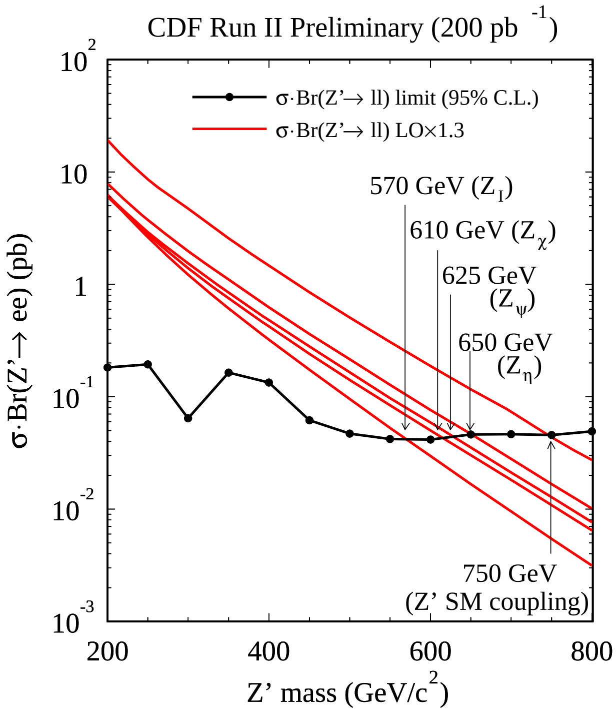

Fig. 6. Upper bounds from 200 pb^{-1} of CDF collected data on the production cross section of a new Z' boson times branching ratio to decay into a di-electron pair. Resulting bounds in several E_6 inspired Z' models are also shown.

	GRW [20]	HLZ [21]						Hewett [22]	
		n=2	n=3	n=4	n=5	n=6	n=7	$\lambda = 1$	-1
CDF Run II	1.06		1.32	1.11	1.00	0.93	0.88	0.99	0.96
DØ Run II	1.36	1.56	1.61	1.36	1.23	1.14	1.08	1.22	1.10
DØ Runs I+II	1.43	1.67	1.70	1.43	1.29	1.20	1.14	1.28	1.14

Table 4. 95% CL lower limits on the ultraviolet cutoff M_S(in TeV) from the Tevatron Run II, within several phenomenological frameworks. NLO QCD effects have been accounted for (signal and background) via a K-factor of 1.3.

the ADD model from 85 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the DØ experiment in the monojet+missing energy channel and for $n = 4, 5, 6, 7$ extra dimensions are 0.68, 0.67, 0.66 and 0.68 TeV correspondingly [16]. The missing E_T distribution is shown in figure 8 [24]. The corresponding spectrum from 84 pb^{-1} from Run I at CDF is shown in figure 9 [23] and the summary of all the results in the

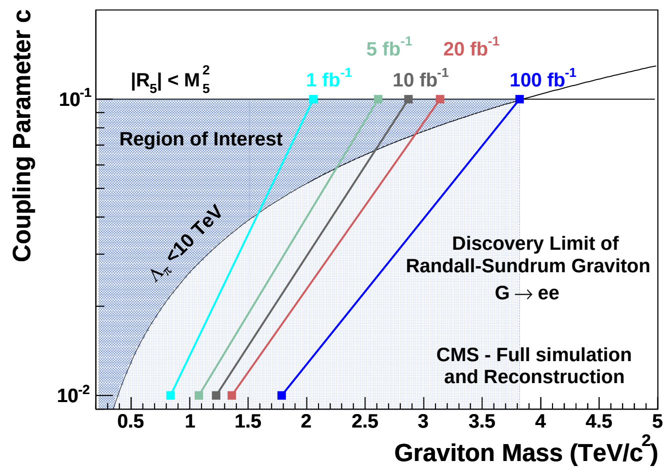

Fig. 7. CMS reach using the di-electron channel for RS gravitons, as a function of the ratio of model parameters c = k/$\mathrm{M_{Planck}}$, and for integrated luminosities between 1 and 100 fb^{-1} [19].

	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$	$n=8$
CDF mono-photons			0.549		0.581		0.602
DØ mono-jets	0.89	0.73	0.68	0.64	0.63	0.62	
CDF mono-jets	1.00		0.77		0.71		

Table 5. Individual 95% CL lower limits on the fundamental Planck scale M_D (in TeV) in the ADD model from the Run I data collected with the CDF and DØ experiments (K=1).

mono-jet and mono-photon [25] analyses from the Tevatron and LEP is shown in figure 10 [16]. Note that LEP is more sensitive for small number of extra dimensions and the Tevatron takes over in sensitivity above 6 extra dimensions, with the jet channel being superior to the photon one.

5 Examples of Beyond SUSY searches at the LHC

The LHC experiments in preparation for the upcoming physics run have developed an extended program of exotic searches. Here is an indicative signature- and model-based listing of Exotics (Beyond the Standard Model and SUSY physics) that is being investigated in LHC's ATLAS (again circa July 2004):

– Jets and Missing ET :

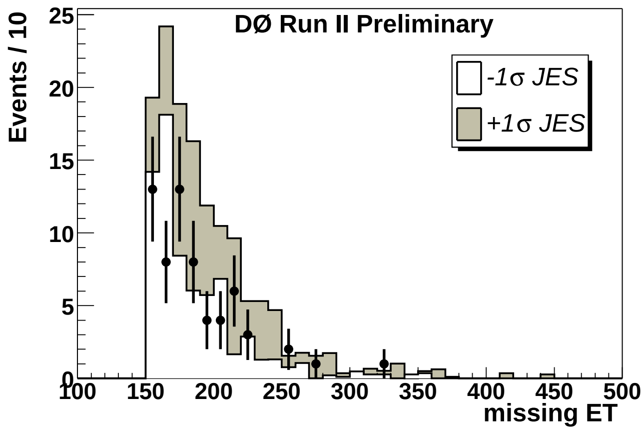

Fig. 8. Distribution of the missing E_T for 85 pb^{-1} of Tevatron data at $\sqrt{s} = 1.96$ TeV, collected with the DØ detector (points) and for non-QCD standard model background. The shaded band indicates the effect of the jet energy scale uncertainties.

  - Signals of models with large extra dimensions in ATLAS
  - Graviscalars in ATLAS

- Narrow Graviton Resonances
- Virtual Graviton Exchange
  - Di-photon, di-lepton, di-jet, $t\bar{t}$ production from virtual graviton exchange
- Radion and other scalars
  - Search for the Randall Sundrum radion using the ATLAS detector
  - Graviscalar in ATLAS
- Gauge Excitations in TeV^{-1} extra dimensions
  - KK excitation of the W boson
  - KK excitations of gluons
- Black Holes
  - Black hole production and decay
  - Search for Gauss-Bonnet black holes
- Trans-Planckian Elastic Collisions
- Singlet Neutrino

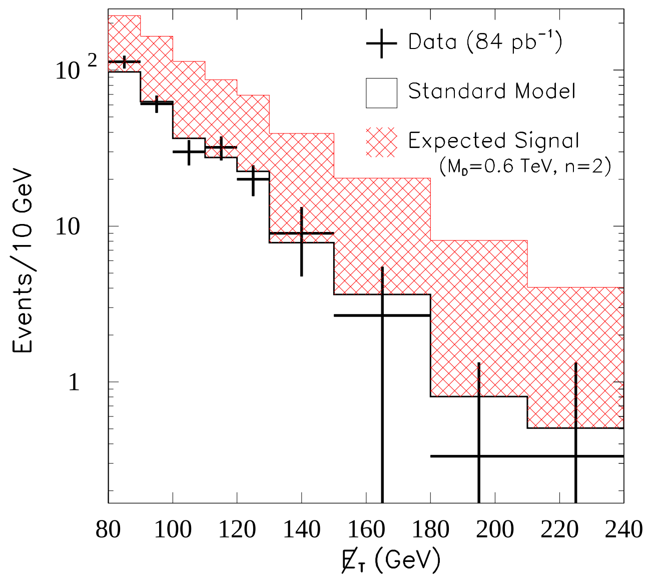

Fig. 9. The predicted missing E_T distribution from Standard Model processes (histogram) and the one from the expected graviton signal (for $n = 2$, $M_D = 0.6$ TeV, and a K-factor of 1.0) added to the Standard Model background (hatched). The signal appears as a smooth excess over the background. The points are the observed data at $\sqrt{s} = 1.8$ TeV collected at CDF Run IB.

   * Hadronic tau decay of a heavy charged Higgs in models with singlet neutrino in large extra dimensions

- Dark energy

   * Dark Energy Signals and Cosmological Constant Signatures in ATLAS (in the contaxt of RS extra dimensions scenarios)

- Universal Extra Dimensions

   * Di-jets in a scenario of Universal Extra Dimensions

6 Remarks

An era of discovery is approaching with the onset of collisions at the Large Hadron Collider. The searches for new phenomena in the currently running Tevatron are setting the stringest limits on many models and with increasing luminosity the exploration of the TeV scale is well underway. The results (of which only a very limited subset is presented here) as well as the problems faced and solved at the

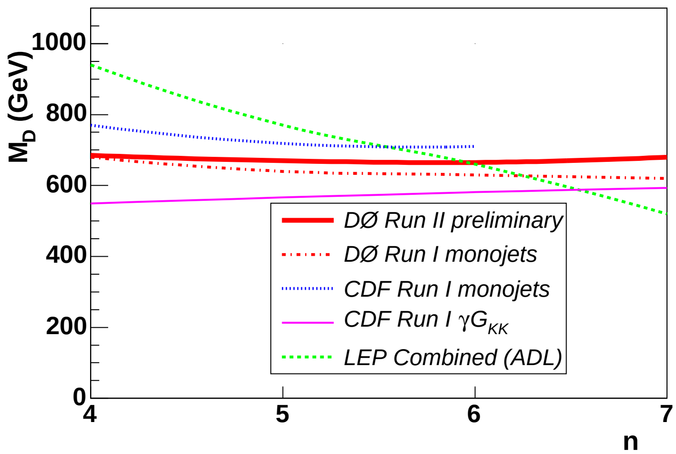

Fig. 10. The limits on the effective Planck scale M_D as a function of the number of extra dimensions from: the Run II D0 monojet analysis (full line), the CDF Run I (dotted line), D0 Run I (dashed-dotted line) and LEP combined (ADL) limit (dashed line).

Tevatron experiments serve in many a case as guides to the strong search and discovery program being developed at the LHC experiments [26].

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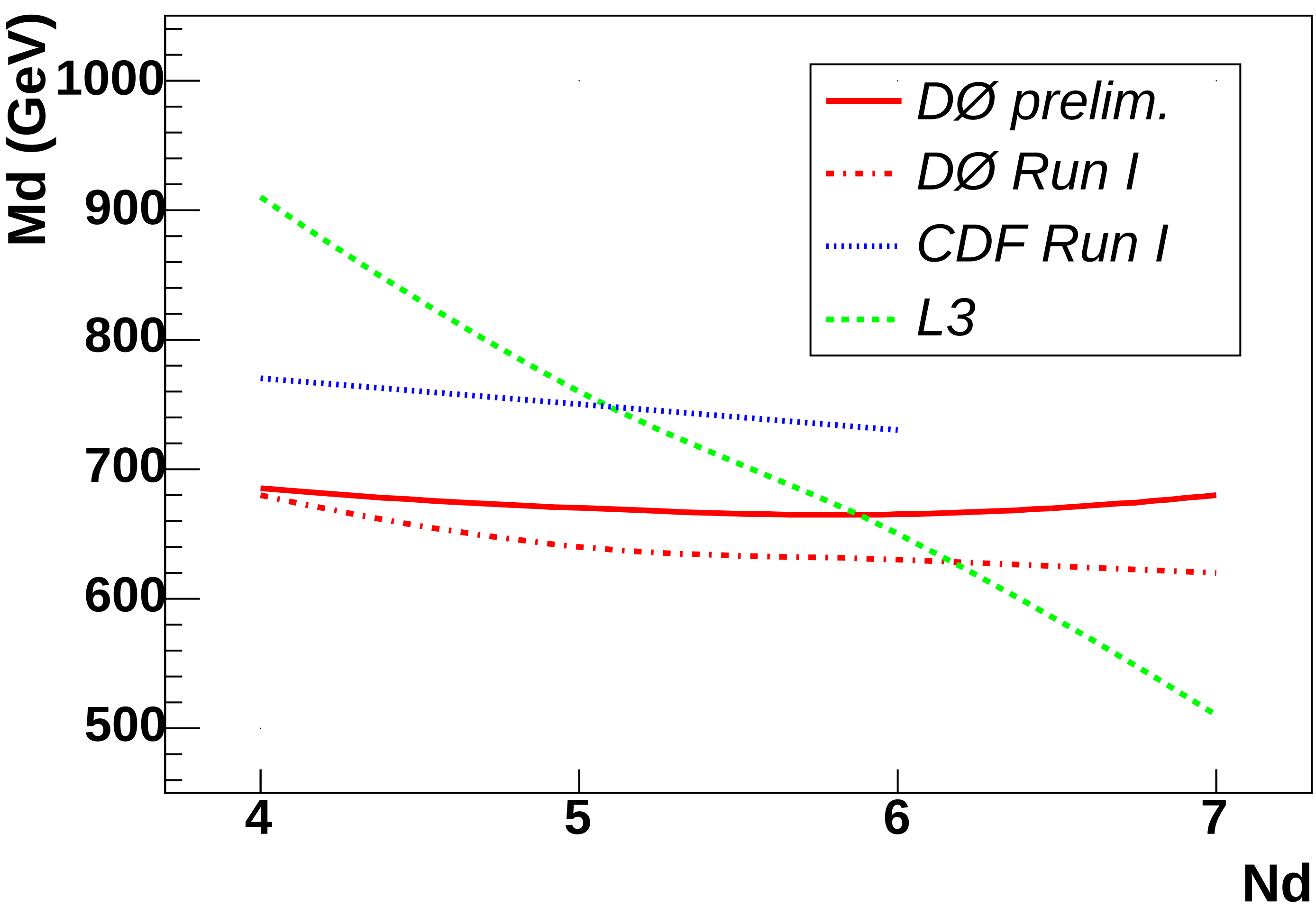
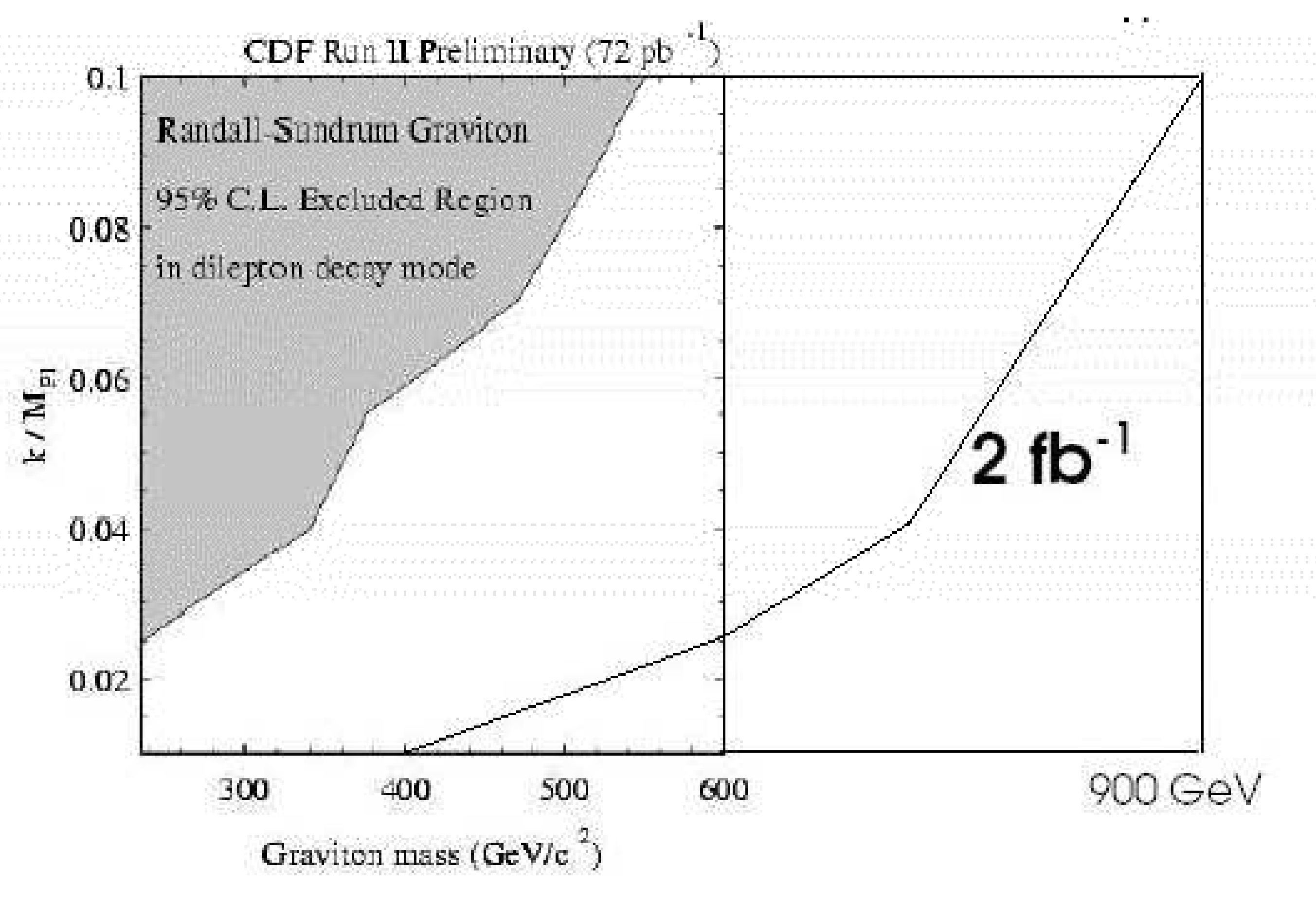


Md (GeV)
1000
900
800
700
600
500
4
5
6
7
Nd
DØ prelim.
DØ Run I
CDF Run I
L3



CDF Run II Preliminary (72 pb^{-1})
Randall-Sundrum Graviton
95% C.L. Excluded Region
in dilepton decay mode
2 fb^{-1}
k / M_{Pl}
0.1
0.08
0.06
0.04
0.02
300
400
500
600
900 GeV
Graviton mass (GeV/c^2)